

A PRECISE GPS-BASED TIME AND FREQUENCY SYSTEM

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Abstract

This paper describes an approach to implementing a compact, highly reliable and precise Master Time and Frequency subsystem usable in a variety of applications. These applications include, among others, Satellite Ground Terminals, Range Timing Stations, Communications Terminals, and Power Station Timing subsystems. All time and frequency output signals are locked to Universal Time via the GPS Satellite system. The system provides for continued output of precise signals in the event of GPS signal interruption from antenna or lead-in breakage or other causes. Cost/performance tradeoffs affecting system accuracy over the short, medium and long term are discussed. A unique approach to redundant system design provides an architecture with the reliability advantage of triple-redundant majority voting and the cost advantages of dual-redundant elements. The system can be configured to output a variety of precise time and frequency signals and the design can be tailored to output as few, or as many, types and quantities of signals as are required by the application.

I. INTRODUCTION

Overview

This paper first presents a background of precise time and frequency generation and briefly lists current-day applications. The GPS system concept is then introduced and the needs in precise frequency and timekeeping that are filled by the GPS system are discussed. Various accuracy alternatives are presented. Next, a practical Station Clock that meets these needs is described. The discussions then proceed to the implementation of a highly reliable, relatively low cost redundant time and frequency system.

Background

The art of precise frequency generation and timekeeping using electronic means has been with us for several decades, with achieved precision steadily improving as new frequency standards and synchronization methods have been developed. Since 1967, the length of a second has been defined in terms of the resonance of the cesium atom, and since the 1970's, cesium beam standards have been used in all applications requiring the most precise frequencies and precise timekeeping. Maintenance of frequency calibration and precise time setting have been a matter of some difficulty

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and great expense, requiring the use of standard frequency radio broadcasts, portable clocks, and extensive manpower allocation. With the advent of the GPS system, ultra-precise frequency generation and timekeeping is with us at immeasurably reduced effort and at a fraction of the costs of previous methods. *When GPS synchronization is used, all generated frequency and time outputs, worldwide, are precisely locked to a common source.*

The GPS system is making all older methods of precise frequency and time generation obsolete and has, with the help of CPU-based instruments, brought precise frequency and timekeeping to a myriad of new applications that could not have afforded the old methods. Present day applications include, among others, the following:

SOME GPS TIME & FREQUENCY APPLICATIONS

- * Satellite ground terminals
- * Communications terminals
- * TV and radio networks
- * Astronomical observatories
- * Electrical power system monitoring
- * Telecommunications systems
- * Cellular radio
- * Frequency-hopping systems
- * Telemetry data acquisition stations

II. GPS CLOCK BASICS

Definitions

The word "clock" has many definitions and connotations. In this paper, we use the term to denote a self-contained electronic instrument that provides a user with precise frequency and (usually) time signals. A GPS Clock is an instrument that synchronizes to GPS to produce precise frequency and time signals. Often, when such an instrument provides all of the signals required at a given site, it is called a GPS Station Clock. Add redundancy, backup power supplies and/or multiple output signal units and we have a GPS Station Clock System (sometimes the word "system" is left off).

Clock Elements

The basic Clock has several necessary elements, as listed below. When only reference frequency outputs are required, the elements related to time accumulation, correction, and generation are not required.

- * A reference frequency source
- * Frequency counters and time accumulators
- * A synchronizing source
- * Time correction mechanisms
- * Output signal generators

Reference Frequency Source

Being self-contained, the Clock has an internal frequency source (oscillator) and, since this paper addresses a GPS-based system, GPS disciplining of the oscillator is assumed. Crystal or rubidium

based oscillators are normally used. A disciplined cesium frequency standard can provide a clock that eliminates almost all the time inaccuracies due to SA. With GPS disciplining, using properly designed disciplining hardware and software, the long term accuracy, i.e.; 24 hours, of the Clock is equal to that of the core GPS system standard. This results from the fact that long-term phase-locked disciplining locks the local oscillator to the GPS standard over the long term and the fact that the core GPS standard does not vary. Loss of GPS disciplining for periods of even several hours does not degrade long term accuracy as long as oscillator-inherent (free running) drift is not excessive, and this can be controlled by selecting a good oscillator for the application.

Now, "long-term" must be defined. With SA active, the resulting signal distortions last from a few seconds to a few hours. The most visible indication of these distortions is a plot of the 1 PPS output of a GPS receiver against a local cesium standard over a period of several days. Experience has indicated that 1 PPS phase returns to "neutral" at intervals not exceeding two-to-three hours and that the summation of deviations integrates to zero over a 16 to 24 hour period. The conclusion is that the accuracy will be on the order of one part in 10^{12} to 10^{13} when measured over a period of 10 to 20 hours.

Reference Frequency Source

Next we come to the situation of expected intermediate term (one second to several minutes) frequency accuracy while tracking satellites. The figure here is determined by the oscillator characteristics. Typically, in this application, voltage control is used to discipline the oscillator, and the disciplining process is one of continually varying the oscillator voltage to track the inherent drifts (primarily aging and temperature stability). The poorer the oscillator stability, the poorer the intermediate term accuracy will be. Ovenized crystal oscillators typically have accuracies in the range of 1×10^{-9} through 5×10^{-11} . Rubidium oscillator accuracy is approximately 1×10^{-11} . Table 1 lists the characteristics for a representative set of oscillators.

Short term stability is totally determined by the oscillator characteristics. Many different suitable oscillators for this application with a great variation of characteristics are available. Data on typical oscillators are given in Table 1.

Knowing the coasting drift is important in some applications. Coasting drift is defined as the total 1 PPS phase drift at the Clock output during those periods when the oscillator is not being actively disciplined by GPS. Since there is worldwide coverage by at least one satellite 24 hours a day, this situation arises only under unusual circumstances, but it is useful information for those cases. Two possible situations where satellite data may not be available are (1) the temporary disconnection of an antenna and (2) the placement of the antenna at a location where all satellites are obscured for periods of time. The coasting drift for various types of oscillators is given in Table 1.

Table 1 gives data for oscillators available from TRAK Systems Division of TRAK Microwave Corporation. If an instrument has accumulated an offset of less than 10 microseconds while drifting, when a satellite is reacquired corrections are applied smoothly to return the phase difference to zero and to reestablish long term accuracy. Conversely, if, at the time of satellite reacquisition, accumulated offset is greater than 10 microseconds, all counters are reset to zero and a new baseline for long term accuracy measurements is established. As can be seen from Table 1, even the least-

precise of

the oscillators offered can withstand greater than four hours without disciplining and still maintain integrity of long term accuracy.

Frequency Counters and Time Accumulators

Clocks of the type described herein contain, as a minimum, the frequency counters to produce a 1 PPS output. Producing a 1 PPS by countdown from the oscillator is required to implement the disciplining process. Figure 1 is a simplified block diagram showing the disciplining circuits.

Clocks producing time of year outputs also contain time accumulators for seconds through years. Modern time Clocks use software accumulators.

Synchronizing Source

As described above, the internal oscillator and 1 PPS output are synchronized to the GPS received 1 PPS signal. The GPS receiver also outputs the data to initially synchronize the time accumulators. It is important to note that, once synchronized, the Clock and its time accumulators can run for periods of many hours without resynchronization. In other words, the Clock does not merely process received GPS data and output it — the Clock uses the GPS received signals for synchronization and, without loss of long term accuracy, bridges periods of no GPS input.

Time Correction Mechanisms

The various time correction factors are described below.

LEAP YEAR: Leap year data for the next century are stored in memory, and proper updating is provided at each year end.

LEAP SECOND: In order to reconcile the time scale produced by the atomic second with the solar scale (Universal Time, UTC), a second is added approximately once a year. This addition is announced in advance and is flagged in the GPS transmission. The internal time clock recognizes this flag and automatically adds one second at the designated time (June 30 or December 31).

TIME ZONE: Many applications use UTC (zero meridian) time regardless of the Clock's location on earth. No adjustments to received GPS time are required in these cases. However, other applications call for local standard time. Provisions are made for front panel or remote computer entry of time zone offset. Once this entry is made, nonvolatile memory maintains the setup data and the Clock automatically produces local standard time.

SUMMER TIME: Some users prefer to correct for and accumulate Summer (or Daylight) time when it is active. Since the dates of change are set by local mandate, provisions are made for front panel or remote computer entry of the required dates. Once these dates are set in for each year, they are stored in nonvolatile memory and corrections are automatically applied at the designated times.

Output Signal Generators

A Clock containing all of the elements described thus far can output a variety of rates and encoded time signals merely by adding circuits that use the basic clock signals to produce the desired outputs. A Clock designed only as a frequency source can output a variety of optional digital and sinewave frequencies. The next section of this paper illustrates a typical GPS Station Clock containing a great variety of outputs.

III. HARDWARE IMPLEMENTATION

A GPS Station Clock

A functional block diagram for a typical production GPS Station Clock incorporating all of the features outlined in the previous paragraphs is illustrated in Figure 2.

On the front panel of a typical GPS Station Clock, keypad and alphanumeric display implement setup of the unit and status display. All desired setups can also be entered by remote terminal or computer. The setup system provides for entering such data as time zone and other optional data differing from default values. Status screens include satellite status, current modes, time and date, latest navigation solution, GPS-lock status, and many others.

Referring to Figure 2, the instrument contains a six-parallel-channel GPS Receiver for frequency disciplining and time presetting, a Disciplined Frequency Subsystem including stable oscillator (crystal or rubidium), a System Processor including receiver interface, executive controller, frequency and time countdown circuits, computer I/O, and other functions. A great variety of signals, including digital rates, sinewave rates, serial time codes, and parallel time codes can be generated and supplied as outputs.

GPS Antenna System

Three primary choices of antenna system exist: (1) passive, (2) active with preamp at antenna and (optionally) in line, and (3) with downconverter at antenna. These are described in the following paragraphs. For lower-accuracy applications, it is possible to mount the GPS receiver in the antenna, but this approach is outside the scope of this paper.

PASSIVE: The GPS frequency of 1.5 GHZ precludes using a passive antenna with more than just a few feet of lead-in cable, and this type of system is restricted to field and vehicular applications.

ACTIVE WITH PREAMP: This is the most common type of system. It is not uncommon to multiplex a dc voltage up the antenna lead-in conductor to power preamps in the line and at the antenna. A well-designed system can use inexpensive coaxial cable to lengths of 200 feet with a preamp in the antenna and to 400 feet with the addition of a line amplifier at midpoint. This distance is more than adequate for most applications. A view of two typical antennas is shown in Figure 4. Lead-in distance can be extended to over 1000 feet using low-loss (expensive and cumbersome) cable and/or additional line amplifiers, but dynamic range decreases with added amplifiers.

DOWNCONVERTER: Lead-in distance can be extended to a few thousand feet if a downconverter is used at the antenna. Typically, the 1.5 GHZ signal is converted to the range of 10-to-80

MHz to greatly reduce cable losses. An upconverter can then be used at the receiver if it has a standard 1.5 GHz front end, or a special receiver made to accept the downconverted frequency can be used. Some systems send an LO signal up to the antenna on a separate cable.

IV. A REDUNDANT TIME AND FREQUENCY SYSTEM

Reliability And Redundancy

The GPS Station Clock and active antenna described above use highly reliable components and the system has a calculated Mean Time Between Failure (MTBF) of 25,000 hours; however, some applications have a required probability of success unachievable with a single unit. This high probability can be achieved by using a well-designed redundant system having only a few single points of failure. For some applications, it is necessary to back up only critical frequency and timekeeping while for others, backup is required for the entire system. All ac power supply paths should have redundancy and/or the primary ac supply should be backed up by batteries. Variations between these two approaches are also used. One quite common variation is described below.

A Practical Redundant System

For many people, the thought of using a redundant system brings visions of a very high expense and a waste of money. However, there are those situations that demand redundancy and, fortunately, redundant timing systems are far less costly today than they were ten years ago. Such a system is described below.

A typical redundant time and frequency system is shown in the block diagram of Figure 3. Two identical GPS Station Clocks (Clock A and Clock B), each with its own antenna, produce all of the types of signals required for system output. All signals from each of the clocks, along with internal status information, are fed to the Fault Sensing and Switching Unit (FSSU).

One exception to using two completely identical Clocks is to use a rubidium oscillator in Clock A and a crystal in backup Clock B; however, the cost savings of this approach hardly justifies the increased logistic costs.

Within the FSSU, the signal set is examined for phase errors, time bit errors, setup bits, and dropouts. The signals from Clock A are placed on line at the outputs of the FSSU. In the event of a signal failure or bad status message from Clock A, the outputs from Clock B are placed on line. Fault lines from other parts of the system are also fed to the FSSU, and any detected system fault is displayed on the FSSU front panel and an audible alarm is sounded.

Each of the signals passing through the FSSU from Clock A or Clock B connects via a simple, highly reliable, switch element. Elements used are reed relays and simple TTL gates. This technique extends the mean time between failure of individual signals at the output of the FSSU to well over 1,000,000 hours.

High-Isolation Low-Noise Frequency Outputs

Some applications demand reference-frequency (typically 5 or 10 MHz) outputs that have very low phase noise and extremely high output-to-output and output-to-input isolation. These are applications where the reference frequencies are being multiplied to much higher frequencies used

by station radars and other equipments. The system architecture shown in Figure 3 provides this isolation. In this approach, the signals to be protected are routed directly from Clocks A and B to a special high-isolation precision frequency distribution unit (FDU). This unit has dual-redundant input buffers followed by a high-isolation electronic switch. Selection of Clock A or Clock B signals is via remote command lines from the FSSU or by local signal dropout detectors in the FDU. Output isolation of greater than 125 dB assures trouble-free system operation. This approach is costly and should be used only if required; however, it can save a lifetime of problems at many radar and communication station applications.

Fault Sensing and Switching Unit

The FSSU, Figure 4, uses an internal reference source (Clock C) to implement digital signal fault location. The unit initially checks for time and phase agreement of Clock A and Clock B outputs. When agreement has been verified, Clock C is synchronized to the agreeing inputs. After this initial synchronization, all of the Clock C frequency dividers and time accumulators free run, using an internal oscillator disciplined to the on-line input Clock. This provides a third independent clock source to continuously check the digital signals against Clock A and Clock B.

The FSSU initially routes Clock A signals to its outputs. In the event of a failure report on the Clock A status line, the detection of a Clock A phase or time difference (vs agreeing Clocks B & C), or a Clock A signal dropout, the FSSU automatically places Clock B signals on line and activates both local and remote alarms. In the event of a failure of Clock B or C, the outputs from Clock A remain on line and the alarms are given.

The FSSU has several features built in to preclude false alarms and switching without sacrificing fault detection capability. For instance, the operator can enter a desired delay time between the detection of a low Status line and declaring a fault. If both status lines go low, a common antenna problem is assumed and automatic switching is inhibited. Provisions are made for properly operating through leap second, leap year, and summer-time corrections and to enter parameters as required.

Another feature of the FSSU is fault collection and alarm for timing buffer units and other units in the system. Also, two RS-232 I/O ports allow for remote setup and status output.

To assure that a single power supply failure does not cause a system failure, the FSSU must be equipped with a dual power supply system, all the way from the power input connectors to the point where the redundant supply lines are diode-OR'ed to the dc busses. The use of a main ac supply with battery backup is discussed further at the end of this section.

Signal Distribution

In modern timing systems, it is not unusual to have requirements for several hundred separately-buffered signal outputs, all designed for driving long, low impedance lines. Most systems also require each buffer module to have fault sensing circuits. As a result, the distribution subsystem often represents one-half of the total Timing Station cost and size. In specifying a system, the engineer must be careful to assure that all significant design considerations and specifications are considered. Space does not permit detailed coverage of this important subject in this paper.

Power Supply System

It is standard practice to provide battery backup for all critical timekeeping circuits or to use uninterruptible ac power sources. This approach protects the system against recovery problems after restoration of primary power; i.e., the Time Base Subsystem does not require several hours. Beyond this, system designers often allow the system outputs to "die", based on the scenario that all of the users of the signals are also without power and that outputs are fully restored upon restoration of station power.

A second consideration is provision for backup of the power supplies within the units. In a redundant system, backup for failed power supplies is mandatory to preclude unnecessary single-point failures. For those units that already have DC power backup, an additional AC power supply is not required for mission success. The FSSU, however, is in a serial path for all signals and must have redundant power supplies. Finally, system reliability is certainly higher if redundant supplies are used in the Distribution Subsystem, but most system designers elect to permit a short down time while a failed TBU power supply is replaced.

Table 1. GPS Clock Oscillator Performance Comparisons

CHARACTERISTICS	STD CRYSTAL	LO DRIFT	LO DRIFT/ REDUCED NOISE	ULTRA LO DRIFT/ LO NOISE	RUBIDIUM
Accuracy while tracking	1 x 10 ⁻⁹	1 x 10 ⁻¹⁰	1 x 10 ⁻¹⁰	5 x 10 ⁻¹¹	1 x 10 ⁻¹¹
Typical coasting drift (first 2 hours)	1.5 us/hr	250 ns/hr	250 ns/hr	150 ns/hr	40 ns/hr
100 sec Allan variance	5 x 10 ⁻¹¹	1 x 10 ⁻¹²	1 x 10 ⁻¹²	1 x 10 ⁻¹²	1 x 10 ⁻¹¹
10 sec Allan variance	1 x 10 ⁻¹⁰	1 x 10 ⁻¹²	1 x 10 ⁻¹²	1 x 10 ⁻¹²	4 x 10 ⁻¹¹
1 sec Allan variance	N/C	5 x 10 ⁻¹²	5 x 10 ⁻¹²	5 x 10 ⁻¹²	1 x 10 ⁻¹⁰
Phase noise @ 1 Hz offset	-80 dBc	-80 dBc	-100 dBc	-100 dBc	-70 dBc
Phase noise @ 10 Hz offset	-85 dBc	-85 dBc	-120 dBc	-120 dBc	-90 dBc
Phase noise @ 100 Hz offset	-100 dBc	-100 dBc	-130 dBc	-140 dBc	-110 dBc
Phase noise @ 1 KHz offset	-105 dBc	-105 dBc	-145 dBc	-155 dBc	-130 dbc
Phase noise @ 10 KHz offset	-115 dBc	-115 dBc	-150 dBc	-160 dBc	-130 dBc
Harmonic distortion	-30 dBc	-30 dBc	-30 dBc	-30 dBc	-40 dBc
Non-harmonic distortion	-40 dBc	-50 dBc	-50 dBc	-60 dBc	-65 dBc

TYPICAL COASTING DRIFT - Oscillator drift when no satellites are in view following two to four days stabilization. Since there is currently full coverage worldwide, this information covers only very unusual conditions.

CHARACTERISTICS	STD CRYSTAL	LO DRIFT	LO DRIFT/ REDUCED NOISE	ULTRA LO/DRIFT LO NOISE	RUBIDIUM
1 hour	1.5 μ s	250 ns	250 ns	150 ns	40 ns
2 hours	3 μ s	500 ns	500 ns	300 ns	80 ns
4 hours	7 μ s	1.5 μ s	1.5 μ s	750 ns	200 ns
8 hours	20 μ s	3 μ s	3 μ s	1.5 μ s	400 ns
16 hours	50 μ s	8 μ s	8 μ s	5 μ s	800 ns

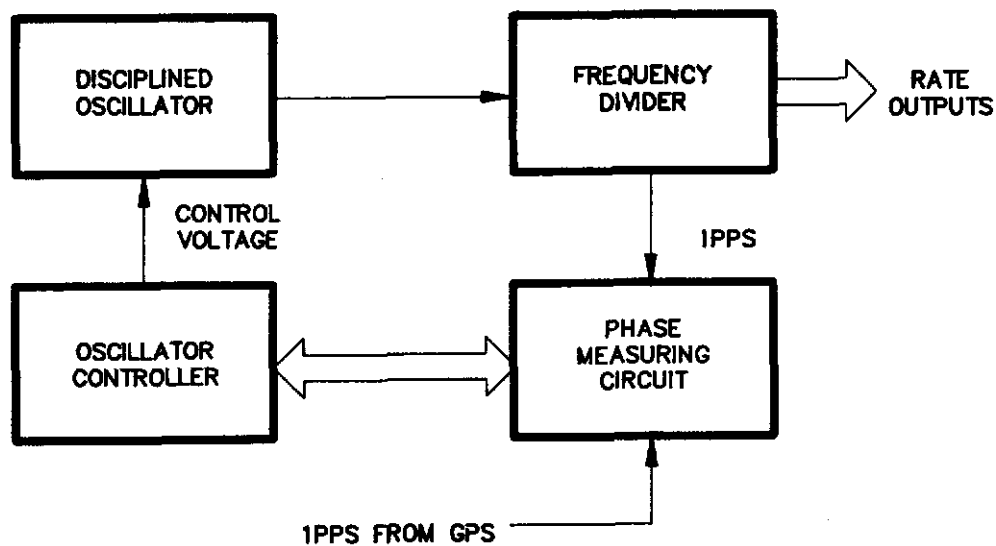


Figure 1. Block Diagram of Disciplining Circuits

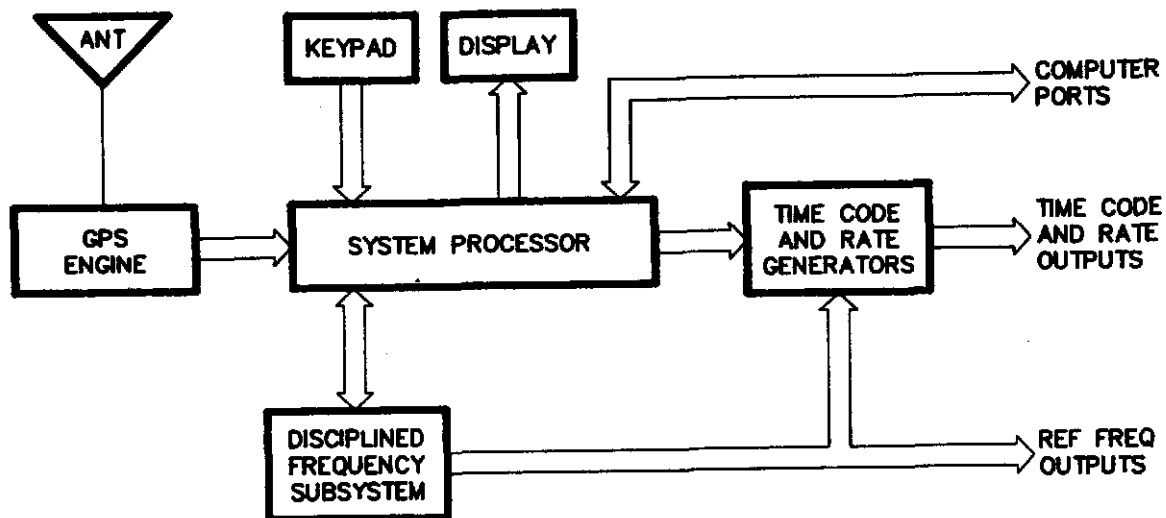


Figure 2. Block Diagram, GPS Station Clock

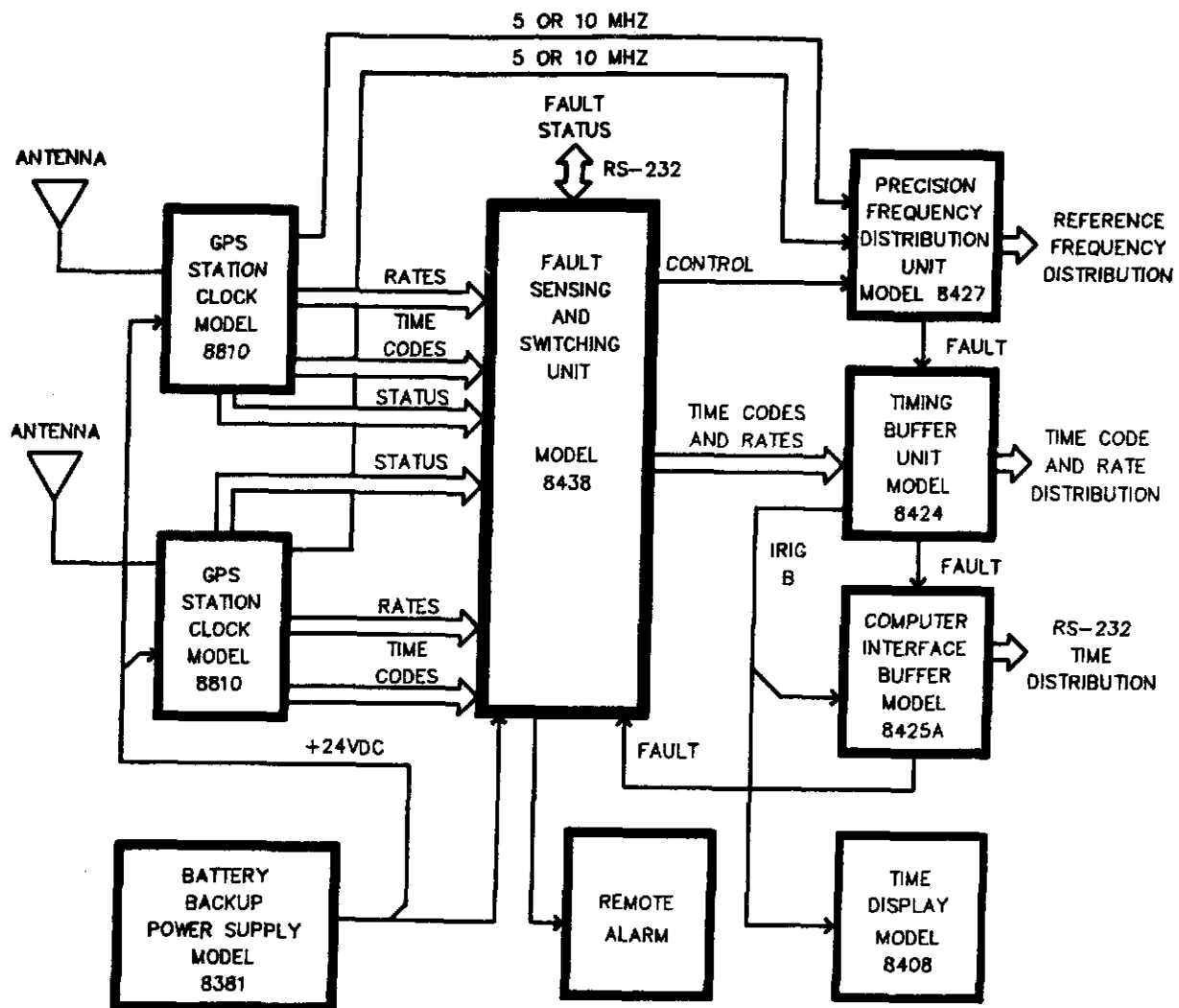


Figure 3. Typical Redundant Timing System

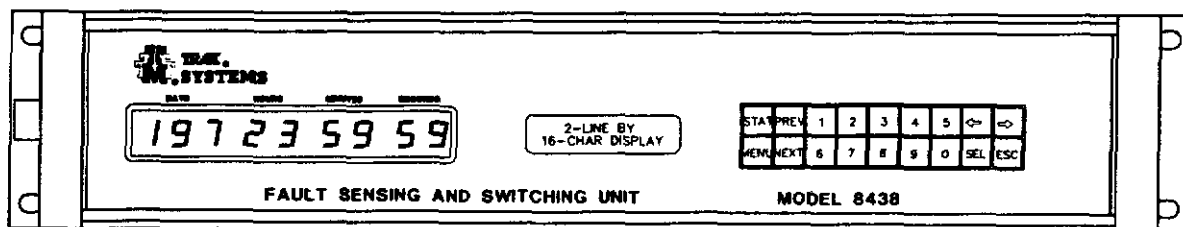


Figure 4. FSSU Front Panel